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XXV.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF
HARVARD COLLEGE.

No. X. — DISTRIBUTION OF MAGNETISM ON ARMATURES.

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THE subject of the distribution of magnetism on armatures has not yet been carefully investigated; although the change of form of the curve due to the addition of an armature has been roughly determined. It appears, that, when an armature is added to one end of a magnet, some of the magnetism spreads over the nearest part of the armature. To prove this, and at the same time to get a general idea of the best way to investigate the subject further, I performed the following preliminary experiment. My apparatus consisted of a steel rod, half a metre long and about a quarter of an inch in diameter, and an iron rod of the same dimensions; also a small wooden bobbin wound with about a hundred and fifty coils of fine insulated wire, and having a hole in its axis just large enough to allow it to slide freely over the rods. A paper scale, graduated into centimetres and millimetres, was attached to each rod. The two ends of the coil of wire were connected with a very delicate galvanometer. The steel rod was magnetized.

The coil was now slipped in different parts of the rod, over a distance of two centimetres each time, and the deflections were noted. This deflection was made the ordinate of a curve, and the abscissa was taken equal to the distance of the centre of the coils at the central point of their motion.

Table I. gives the figures, which are, of course, only relative. The distances are given in centimetres.

TABLE I.

SIMPLE MAGNET. PRELIMINARY EXPERIMENT.

Distances (Cm.).	Deflections.	Distances (Cm.).	Deflections.
0.5	+ 9.6	29.5	— 0.6
2.5	7.8	31.5	1.4
4.5	6.2	37.5	2.45
6.5	5.	40.5	4.2
8.5	4.1	42.5	4.9
10.5	3.7	44.5	6.7
12.5	3.0	46.5	8.6
15.5	2.0	48.5	9.0
19.5	1.1	49.5	10.0
23.5	0.35	1.	
25.5	0.23		
27.5	0.		

When the armature was added, the distribution on the magnet was as in Table II. *a*. Here, too, the numbers represent only relative values. Table II. *b* gives, in the first column, the distances; in the second, the permanent magnetism of the armature (nearly constant after once touching the magnet); in the third column, its magnetism when the magnet was attached; in the fourth, the difference of the second and third; in the fifth, the value corrected as afterward to be explained.

TABLE II.

MAGNET AND ARMATURE. PRELIMINARY EXPERIMENT.

a. THE MAGNET.

Distance.	Deflections.	Distance.	Deflections.	Distance.	Deflections.
0.5	+9.1	19.5	+1.25	34.5	—1.4
2.5	8.3	22.5	0.6	36.5	2.0
4.5	6.5	24.5	0.4	38.5	2.9
6.5	5.3	26.5	0.2	40.5	3.2
8.5	4.4	27.5	0.	42.5	4.
10.5	3.7	28.5	—0.2	44.5	4.5
12.5	2.9	30.5	0.5	46.5	5.
15.5	2.1	32.5	1.0	48.5	5.7

b. THE ARMATURE.

Distances from juncture.	Deflection due to permanent magnetism.	Deflection when bar was added.	Difference of last two columns.	Corrected values for ideal armature.
50.5	+ 0.15	—4.2	—4.35	—4.28
52.5	— 0.05	3.7	3.65	3.65
54.5	0.15	2.2	2.05	2.05
56.5	0.2	1.8	1.6	1.6
58.5	0.2	1.2	1.0	1.0
60.5	0.2	1.0	0.8	0.8
62.5	0.2	0.75	0.55	0.55
65.5	0.15	0.6	0.45	0.45
69.5	0.065	0.3	0.24	0.25
74.5	0.045	0.18	0.18	0.18
80.5	+ 0.10	0.03	0.13	0.16
84.5	0.17	0.01	0.18	0.14
86.5	0.20	+ 0.08	0.12	0.13
92.5	0.26	0.05	0.11	0.12
97.5	0.20	0.06	0.12	0.11

The last three values of the curve of magnet, under *a* should be corrected so as to read,

Distance.	Deflection.
44.5	6.7
46.5	5.4
48.5	6.4

It is evident from this experiment, 1st, That the magnetism spreads over the armature.

2d, That the zero point is almost immovable. This was proved repeatedly with various magnets and armatures; and even the most delicate test possible—that of testing the change of distribution at the zero point, when the armature was suddenly removed, by the current induced in a helix—even this failed to show more than the very slightest change.

3d, That the whole farther end of the magnet is unaffected by the armature. This was tested and proved in the same way.

4th, That probably the permanent magnetism of the armature should

be subtracted from the total magnetism of the armature when in contact with the magnet; and when the two are nearly equal, as a small error in observation will produce a large relative error in the result, any small irregularities should be removed from the curve. When, however, there is any quantity of permanent magnetism at the juncture, and of an opposite sign to that of the magnet, allowance should be made for a portion of this magnetism spreading over the magnet. The law by which this happens will be demonstrated by and by. It is the same, nearly at least, as if the magnet were soft iron. About half of this magnetism, therefore, spreads over the magnet. Unless this counter-distribution be taken into account, it will be absolutely impossible to obtain accurate results; for no bar of soft iron used as an armature will remain free from permanent magnetism, even if it were perfectly non-magnetic before.

I next investigated the change due to closeness of contact, and found that a bar with perfectly flat ends varied in the amount of magnetism it drew from a magnet ten to twenty per cent, according to the means taken to secure perfect contact of surfaces.

The amount drawn off varies with the length. Some idea of the proportion may be given by these numbers. 100 units being the amount drawn off by a metre bar from a metre magnet, a bar a metre and a half long would draw off about 135 units; half a metre long, 80 units; and 9 cm. long, about 30 units. A mass of iron in weight equal to 116 cm. of iron rod of the size used above draws off about 65 units; so that the length makes a much greater difference than the mass. When for a solid rod we substitute a bundle of wires of equal length and weight, there is no sensible difference in the amount of magnetism drawn off, as tested by the current induced in a helix.

The old apparatus was now laid aside. The new one differed in several respects. The bobbin was of brass; thickness outside, $5\frac{1}{2}$ mm.; inside, 3 mm.; depth of cut was about $5\frac{1}{2}$ mm.; and the diameter of the rods was 12 mm. The magnet and armature had a small hole bored in each end, and a small screw was fitted to draw them tightly together. The surfaces of the ends were made perfectly flat in a lathe. Two clamps served to limit exactly the motion of the bobbin to any distance desired. The magnets and armature were placed east and west on a table about eight metres from the galvanometer, whose deflections were observed with a telescope. Therefore both the induced magnetism of the earth was eliminated, and the magnet had but little effect upon the galvanometer.

Table III. gives the magnetism of magnet No. 1 reduced to absolute measure by the following formula:—

Let n = number of coils in helix.

n' = number of coils in earth inductor.

R = radius of earth inductor in centimetres.

K = the intensity of earth's magnetism ($=$ about $\frac{1.7}{\cos 73^\circ}$),

A = deflection of galvanometer by helix.

B = deflection of galvanometer by earth inductor.

dL = the distance over which the helix was slipped.

M = the surface magnetism of the bar at the point to be measured, the unit being that quantity which will produce unit field at unit distance, then $M = \frac{A}{B} \frac{n'}{n} \frac{R^2 K}{dL}$ (for all points except very near the ends).

Table III. shows the magnetism of magnet No. 1, and armature in terms of K .

TABLE III.

a. THE ARMATURE.

Distances from juncture.	Permanent magnetism.	Magnetism when attached to magnet.	Difference of last two columns.	Values corrected for contra-distribution.*
98	+4.0	+3.0	+1.0	
92	4.5	2.97	1.7	
81½	5.1	3.8	1.5	
71½	6.2	4.5	1.7	
61½	7.3	4.9	1.9	
51	8.5	5.5	3.0	
41	13.9	8.3	5.6	
30½	16.3	7.25	9.1	
20½	18.8	0.12	18.7	
10½	21.2	—5.3	26.5	+24.0
5½	21.2	16.5	37.8	29.5
1½	17.0	27.2	44.2	30.5

* That is the distribution of the permanent magnetism of the armature upon the magnet.

b. THE MAGNET.

Distances from juncture.	Magnetism corrected for contra distribution.*	Distances from juncture.	Magnetism corrected for contra distribution.*
2½	56.	18½	45.5
3	57.	28½	29.7
5	54.5	39	15.
8	54.	49	0.
11½	53.5	59	—22.
14½	53.	74½	44.
13½	52.	84	67.
16½	50.	94	109.
15½	48.	98	162.

Table IV. gives the distribution for a hollow tube of soft iron (one metre in length) magnetized by a core of steel wires extending half way down the tube. The magnetism was obtained by halving the difference of the two values obtained before and after reversing the magnetic core.

TABLE IV.

HOLLOW TUBE WITH MAGNETIC CORE.

Distances (Cm.).	Magnetism.	Distances.	Magnetism.
2½	—12.	49½	5.85
10½	— 5.5	56	4.0
20½	— 1.8	61	2.9
31	+ 1.05	71	1.35
41	4.2	81½	0.52
44	5.5	91½	0.2
46	5.55		

Last of all, let us examine the case of two magnets joined by their opposite poles.

* That is the distribution of the permanent magnetism of the armature upon the magnet.

Without going through the process of analysis, let me simply state what seems to me to be the truth.

Each magnet probably distributes upon the other as much magnetism as it would were a *steel* bar, without magnetism, in the place of the other magnet; and this amount is about one-half or two-thirds the amount that would be distributed on a bar of soft iron. The resulting distribution is simply the algebraic sum of its components.

Table V. gives the magnetism actually observed; and it is remarkable, that, if these curves are plotted, the very same line that represents the theoretical represents also the observed magnetic curve for this case. I would state that the curves were not chosen to suit the occasion, but are identical with the curve of the preliminary experiment, where the poor juncture or the shortness of the bar made up for the superior capacity of the soft iron.

Whether the theory be true or not, I leave it to be judged. It is at least useful in eliminating the contra-distribution inevitable in experimenting with soft-iron armatures; for, if the law holds so nearly in case of such large values, the error in small values must be inappreciable.

The law is as follows: *Find the curve of the armature when a perfectly non-magnetic bar of soft iron, of half the length of the magnet, is joined to it; then subtract algebraically this magnetism from the observed.*

TABLE V.

DISTRIBUTION OF TWO MAGNETS UNITED BY OPPOSITE POLES.

Magnet No. 1.		Magnet No. 2.	
Distances from juncture.	Magnetism.	Distances from juncture.	Magnetism.
0	+ 2.0	0	+ 2.
10	—29.0	10	36.
15	37.0	15	37.
20	37.0	20	36.
30	31.0	30	24.
50	1.5	50	— 2.5
98	151.0	98	130.

In the case of two similar poles being brought together, there is no perceptible change of distribution: the most delicate experiments failed to show any. Probably a change does, however, take place; but the resulting curve is so like the former curve, that the difference is imperceptible.

On the theory of the analogy of the magnetic lines of force to electric currents, these laws will, I think, be nearly, though not completely, fulfilled.

These laws, if true, and, if not, in so far as they are true, enable one to determine the shape which the curve would assume were the armature and magnet of one piece of metal; i.e., if the juncture was absolutely perfect.

Moreover, the same method enables us to draw the limiting values for different lengths of armature: for we have only to increase each abscissa of the curve of the magnet as the total length of magnet and armature is to that of the magnet alone, and to take the half-sum and half-difference as before, to find the curves on the magnet; then, drawing a curve in the same manner to represent another magnet of length of armature joined by a similar pole, the curves on the armature can thus be determined. We shall see, then, that a soft-iron armature acts like a steel armature of about double the length. Whether this is due to contra-distribution, or to a superior magnetic capacity, I leave to be determined.

The following experiments were devised to show the change in magnetic moment due to armatures. The experiments are rough; but they give far the best idea of the changes that take place in magnetic distribution. A magnet was placed upon the floor at a fixed distance from the galvanometer-needle, to the east of it, and pointing east and west. Then an armature was added, and the position of the centre of the magnet was marked upon the floor. Then the whole combination was removed to a distance, and the deflection was noted. Then the combination was brought back, with poles reversed, and was moved toward the galvanometer till the deflection was equal to the previous one.

This at once showed the increase of distance between the poles; for it must have been equal to the distance of the centre of the magnet from its former position, and the central point must have advanced half this distance. Having determined the position of the central point, the magnet alone was now turned upon it; and the ratio of the deflection of the magnet and armature to that of the magnet alone showed the change of magnetic moment.

The centre of the longest armature (150 cm.) advanced 18.25 cm., and the moment became half as much again. The centre of the metre armature advanced 14.5 cm., and its moment became a little over quarter as much again. The moment of the short (50 cm.) armature was increased one-sixth.

From this the distance of the poles of the magnet from the ends can be calculated; and it is about 12 cm. When calculated by the vibrations of a compass in two positions very near the end, it appeared to be 5 cm.: the latter method is probably, therefore, inexact, and will always give the distance too small. It is only at large distances that the magnetism of one end of a bar can be considered as acting at a point.

When the magnet was joined to the armature by a short piece of iron shaped like a U, so that it was parallel to the armature, the pole apparently retreated about 7 cm., and the moment decreased about one-tenth. When, however, a second U armature was added to complete the circle, the reduction of magnetic moment was scarcely perceptible, being less than $\frac{1}{34}$ of the total value. This may possibly be due to poor contact; but I was unable to obtain any different result, though I measured the distribution in various ways. Perhaps, when the armature is bent round so near the magnet, the resistance of the air to the line of force is so slight, that the adding of the second armature affects it but little. This, I think, would be the necessary consequence of the analogy of magnetic force and electric currents.

We see, then, that shunting, so to speak, the poles of a magnet with a soft-iron bar, diminishes the magnetic moment about one-sixth.

It follows, that, if a stronger magnet be shunted by a weaker one, the magnetic moment will be diminished in some way proportional to the difference of magnetization. This accounts for the fact that thick magnets are weaker than an equal weight of thin ones: 1st, because it is impossible, owing to the difficulty of tempering evenly, to obtain the maximum capacity for magnetism in all parts of the bar, and those parts which are weaker diminish the average magnetism per weight, and also diminish the strength of the stronger parts, acting like a shunt; 2d, because, in the common process of magnetizing a bar by rubbing the surface, the interior is less magnetized than the outside, and the core acts more or less like a shunt of soft iron.

If, however, a solid body is magnetized by a force acting on all parts alike, it will not act differently from a bundle of wires of equal length and weight, provided the material be the same. Therefore the bundle

of iron wires alluded to above ought to act, as they did, like the solid bar. Fact and theory agree. I am now prepared to answer a question, from which, curiously enough, the whole of the present investigation sprang. I can answer decidedly that there will be no advantage in substituting a bundle of iron wires or plates for the solid core of the helix of a magnetic engine; but, as the helix will be farther off from the core, the induced current will not be increased, but diminished.